

Confirmation of the binary status of Cha H α 2 - a very young low-mass binary in Chamaeleon[★]

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ABSTRACT

Context. Neuhauser & Comerón (1998, 1999) presented direct imaging evidence, as well as first spectra, of several young stellar and sub-stellar M6- to M8-type objects in the Cha I dark cloud. One of these objects is Cha H α 2, classified as brown dwarf candidate in several publications and suggested as possible binary in Neuhauser et al. (2002).

Aims. We have searched around Cha H α 2 for close and faint companions with adaptive optics imaging.

Methods. Two epochs of direct imaging data were taken with the Very Large Telescope (VLT) Adaptive Optics instrument NACO in February 2006 and March 2007 in Ks-band together with a Hipparcos binary for astrometric calibration. Moreover, we took a J-band image in March 2007 to get color information. We retrieved an earlier image from 2005 from the European Southern Observatory (ESO) Science Archive Facility, increasing the available time coverage. After confirmation of common proper motion, we deduce physical parameters of the objects by spectroscopy, like temperature and mass.

Results. We find Cha H α 2 to be a very close binary of ~ 0.16 arcsec separation, having a flux ratio of ~ 0.91 , thus having almost equal brightness and indistinguishable spectral types within the errors. We show that the two tentative components of Cha H α 2 form a common proper motion pair, and that neither component is a non-moving background object. We even find evidence for orbital motion. A combined spectrum of both stars spanning optical and near-infrared parts of the spectral energy distribution yields a temperature of 3000 ± 100 K, corresponding to a spectral type of $M6 \pm 1$ and a surface gravity of $\log g = 4.0^{+0.75}_{-0.5}$, both from a comparison with GAIA model atmospheres. Furthermore, we obtained an optical extinction of $A_V \approx 4.3$ mag from this comparison.

Conclusions. We derive masses of $\sim 0.110 M_{\odot}$ ($\geq 0.070 M_{\odot}$) and $\sim 0.124 M_{\odot}$ ($\geq 0.077 M_{\odot}$) for the two components of Cha H α 2, i.e., probably low-mass stars, but one component could possibly be a brown dwarf.

Key words. Stars: low-mass, brown dwarfs – binaries: close – binaries: visual – Stars: individual: Cha H α 2

1. Introduction

Neuhauser & Comerón (1998) found Cha H α 2, also called ISO-ChaI 111, to be a member of the Cha I star-forming cloud with an age of ~ 2 Myr. Neuhauser & Comerón (1999) then classified Cha H α 2 as a candidate brown dwarf of spectral type M6.5, using medium-resolution optical spectroscopy. Comerón et al. (2000) presented evidence for near- to mid-infrared excess indicating a disk. Natta & Testi (2001) and Apai et al. (2002) argued that the spectrum can be explained with an optically flat dust disk, but not with a flared disk, due to lack of any prominent silicate feature previously expected for the disk of Cha H α 2. Neuhauser et al. (2002) searched for companions around Cha H α 1-12 with the Hubble Space Telescope and presented the first indication for binarity of Cha H α 2 due to elongation of the Point Spread Function (PSF) in filters R and H α .

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[★] Based on observations made with ESO telescopes at the Paranal Observatory under programme IDs 076.C-0292A, 076.C-0339B, 078.C-0535A, at the La Silla Observatory under programme ID 065.L-0144B, the Hubble Space Telescope under programme ID GO-8716 and on observations made with the European Southern Observatory telescopes obtained from the ESO/ST-ECF Science Archive Facility.

The rotational period of 3.21 ± 0.17 days, found in photometric data by Joergens et al. (2003), confirmed the spectroscopic period of $2.9^{+1.4}_{-1.0}$ days already proposed in Joergens & Guenther (2001). Natta et al. (2004) observed nine stars in the Cha I dark cloud and found only at Cha H α 2 signs of accretion in H α and Pa β , making it the only object out of nine to show clear signs of accretion at a rate of $\sim 10^{-10} M_{\odot}/\text{yr}$ and an inclination of ~ 65 to 75° . Observations with XMM-Newton by Stelzer et al. (2004) revealed X-ray emission from Cha H α 2. Recently, Apai et al. (2005) succeeded in using new infrared spectra to conclude that the disk around Cha H α 2 is still closer to the flat disk model, even though a prominent enstatite silicate feature could be found at $9.3 \mu\text{m}$.

Here, we present evidence for the binarity of Cha H α 2. In Sects. 2 & 3, we present the observations, data reduction, and astrometric results. The available photometric properties of both components will be discussed in Sect. 4. The spectroscopy of the system is presented in Sect. 5. We end with conclusions in Sect. 6.

2. Observations with VLT/NACO

We observed Cha H α 2 in two epochs in February 2006 and in March 2007, see Table 1 for the observations log. Included in Table 1 are the data found in the archive from March 2005.

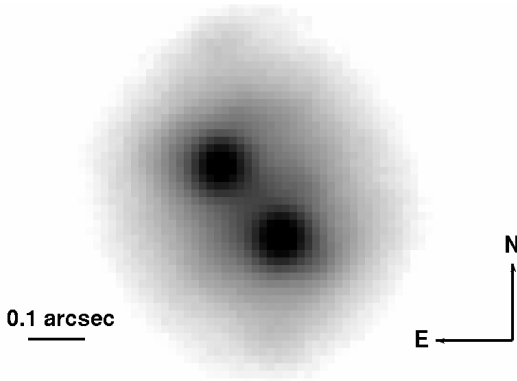


Fig. 1. NACO Ks-band image of the low-mass binary Cha H α 2 from 25 March 2005. The southwestern component appears slightly brighter, hence we call this component A (or SW), the fainter northeastern component B (or NE).

Table 1. VLT/NACO observations log

JD - 2453400 [days]	Date of observation	DIT [s]	NDIT	No. (a) images	Filter
54.62360 (b)	25 Mar 2005	30	2	23	Ks
382.67884	16 Feb 2006	10	6	20	Ks
760.70760	1 Mar 2007	60	2	15	Ks
761.66193	2 Mar 2007	30	2	24	J

Remarks: (a) Each image consists of the number of exposures given in column 4 times the individual integration time given in column 3. (b) Retrieved from the ESO Science Archive Facility.

Table 2. Proper motions of Cha H α 2

Source	PM RA [mas/yr]	PM DEC [mas/yr]
USNO-B1 (a)	-20 ± 17	-14 ± 4
PSSPMC (b)	-23 ± 17	$+1 \pm 17$
SSS-FORS1	-19.4 ± 14.9	-0.3 ± 14.9
SSS-SofI	-23.0 ± 14.1	$+7.8 \pm 14.1$
Mean	-21.8 ± 8.8	$+3.2 \pm 8.8$

Remarks: (a) This value (Monet et al. 2003) was not used in the final proper motion due to its unreasonably small error of PM in declination, which makes it inconsistent with the measurements using the SuperCOSMOS Sky Survey in comparison to data from the New Technology Telescope (NTT) instrument Son of ISAAC (SSS-SofI). (b) From the Pre-main Sequence Stars Proper Motion Catalog (Ducourant et al. 2005).

We observed with the European Southern Observatory (ESO) Very Large Telescope (VLT) instrument Naos-Conica (NACO, Lenzen et al. 2003; Rousset et al. 2003). DIT, NDIT, NINT, and filter bands are listed in Table 1. In all cases, we used the S13 camera (~ 13 mas/pixel pixel scale) and the double-correlated read-out mode.

For the raw data reduction, we subtracted a mean dark from all the science frames and flatfield frames, then divided by the mean dark-subtracted flatfield and subtracted the mean background using *eclipse/jitter*.

In all three images, Cha H α 2 is clearly resolved in a double object with an apparent separation of ~ 160 mas at a position angle of $\sim 40^\circ$, see Fig. 1. The southwestern component appears slightly brighter, hence we call this component A (or SW), the fainter northeastern component B (or NE).

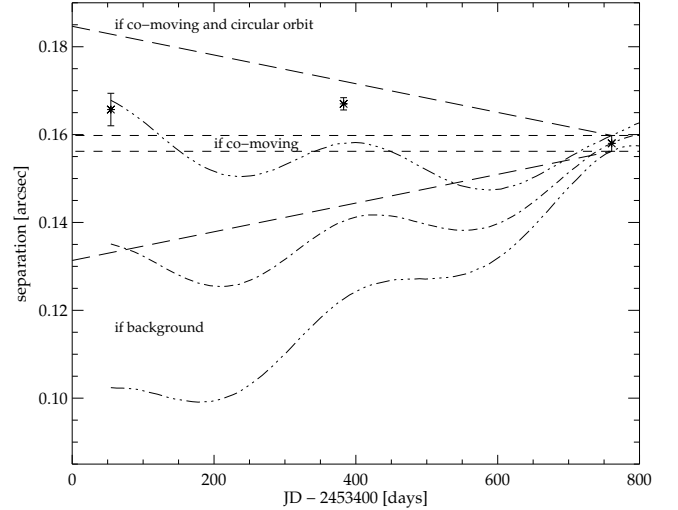


Fig. 2. Observed separation between the two components of Cha H α 2. The archival data point from 2005 and our two measurements from 2006 and 2007 are shown. The short-dashed lines enclose the area for constant separation. The dash-dotted line is the change expected if the B component is a non-moving background star. The opening cone enclosed by the dash-dotted lines with more dots are its estimated errors. The waves of this cone show the differential parallactic motion, which has to be taken into account if the other component is a non-moving background star. The opening long-dashed cone indicates the amplitude of possible orbital motion.

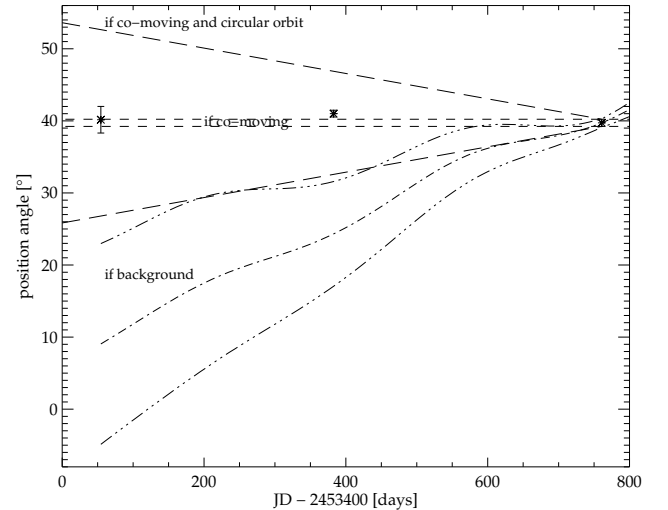


Fig. 3. Observed position angle between the two components of Cha H α 2 (measured from the brighter component north over east to south). See Fig. 2 for details.

3. Astrometry

To check for common proper motion of the two tentative components of Cha H α 2, we used the proper motion (here PM) of Cha H α 2 published in the literature (USNO-B and PSSPMC); we calculated additional values by comparing SuperCOSMOS Sky Survey (here SSS) data from 1985 with images from VLT/FORS1 (epoch 1999, published by Comerón et al. 2000, obtained directly from F. Comerón, priv. com.) and New

Table 3. Astrometric calibration and astrometric results for Cha H α 2 AB

JD - 2453400 [days]	Calibration binary	pixel scale [mas/pixel]	orientation [deg]	JD - 2453400 [days]	Target	separation [mas]	PA (a) [deg]
54.76919	HIP 73111	13.22 ± 0.28	-0.17 ± 1.84	54.62360	Cha H α 2 AB	165.7 ± 3.7	40.16 ± 1.84
388.84537	HIP 73357	13.24 ± 0.07	0.18 ± 0.46	382.67884	Cha H α 2 AB	167.0 ± 1.4	41.01 ± 0.47
760.76369	HIP 73357	13.24 ± 0.07	0.34 ± 0.46	760.70760	Cha H α 2 AB	158.0 ± 1.8	39.73 ± 0.50

Remarks: All Ks-band images. (a) PA is measured from N over E to S. 180 deg to be added to position angle (PA) if seen from fainter component.

Technology Telescope instrument Son of ISAAC (NTT/SofI) from 2000, observed by us ($10 \times 50 \times 1.2$ second integrations), reduced in the same way as the NACO data with eclipse. See Table 2 for the results (originally from Gaedke (2005), but revised here by us). We use the mean proper motion for checking, whether the two objects show common proper motion below.

We calibrated the NACO data using the wide binary star HIP 73357 for our two measurements in 2006 and 2007, and the closer binary HIP 73111 for which we found archived data taken in the same night as the Cha H α 2 observations in 2005, resulting in the astrometric calibration summarized in Table 3. The error bars of pixel scale and orientation include, possible orbital motion of the respective binary since its measurement by Hipparcos – i. e., a maximum change in separation due to possible orbital motion for circular edge-on orbit and a maximum change in position angle for circular pole-on orbit – as well as the uncertainties in parallax, total mass, position measurements in our images and separation at the epoch of Hipparcos of the respective binary system.

To determine the positions of both components we constructed a reference PSF from the binary itself by using the undeformed remote sides of both objects shifted to the same peak position. Thus, we obtained a clean reference PSF for each single image. With IDL/starfinder, we scaled and shifted the reference PSF simultaneously to both components in each of our individual images by minimizing the residuals. As a result, we obtained positions (see Table 3) and relative photometry (see Table 4), including realistic error estimates for each object by averaging the results of all single images taken within each epoch.

The development of separation and position angle with time is shown in Figs. 2, 3, 4, and 5. We can exclude by 0.9σ & 1.5σ (Fig. 2); 2.2σ & 2.3σ (Fig. 3); 1.4σ & 1.0σ (Fig. 4); 2.1σ & 1.9σ (Fig. 5) that either one of the tentative components of Cha H α 2 is a non-moving background object. Viz, for both components the background hypothesis is rejected by $\geq 3.7 \sigma$, respectively. For two objects slightly above the sub-stellar mass limit (see below) and the given separation (at ~ 168 pc), the orbital period is ~ 110 yrs, so that the maximum change in separation due to orbital motion (for circular edge-on orbit) is ~ 12 mas/yr ($\sim 3^\circ$ /yr in PA for pole-on orbit). While orbital motion could be detected in PA only from one point in 2006 in contrast to 2007, with 1.9σ significance, we detect orbital motion as deviation of the separation in 2005 and 2006 in contrast to the 2007 measurement, with 1.9σ & 3.9σ significance. From the negligible change in PA during our ~ 2 years of epoch difference, we can exclude a circular pole on orbit by 2.8σ , however, we cannot rule out a highly eccentric pole-on orbit.

In Fig. 7, the data from Hubble Space Telescope by Neuhauser et al. (2002) are also included. Only the plot for the assumption of component B being a non-moving background star is shown here. The Hubble Space Telescope data hence yield another 2.2σ & 2.3σ for component A & B not being a non-moving background star, respectively.

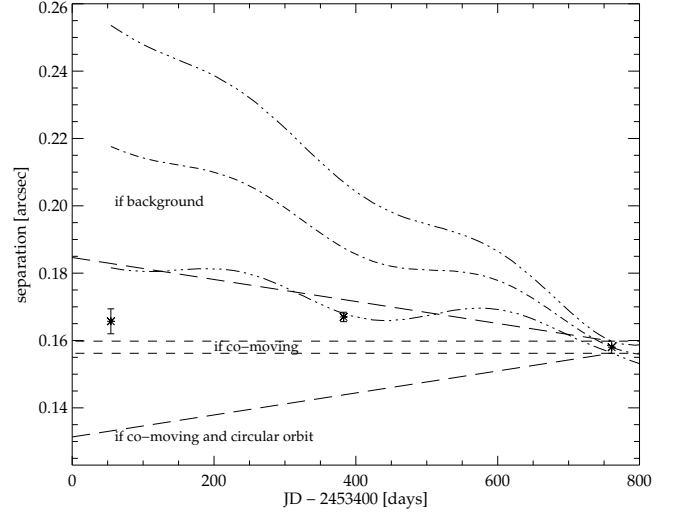


Fig. 4. Observed separation between the two components of Cha H α 2. Same as Fig. 2, but the opening cone enclosed by the dashed-dotted lines is the change expected if the A component is a non-moving background star.

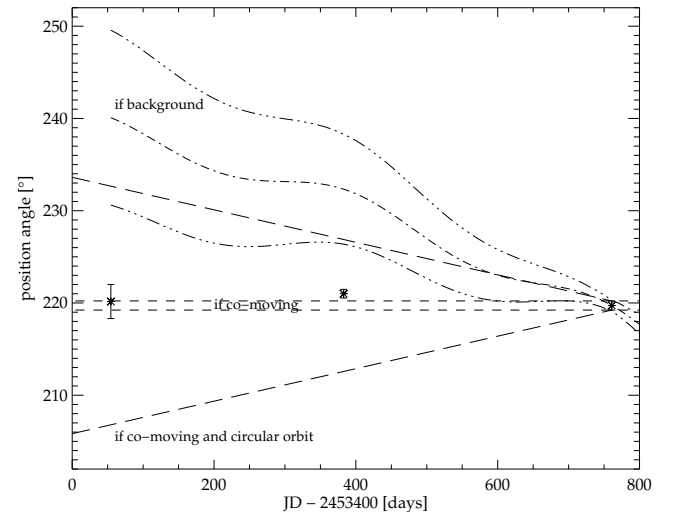


Fig. 5. Same as Fig. 3, but position angle between the two components measured from the B component and assuming the A component is a non-moving background star.

While the difference seen in PA and the separation between the different observations are consistent with common proper motion and some orbital motion, a possible difference in proper motion between both objects of up to a few mas/yr cannot be excluded from the data. Such a difference in proper motion is typi-

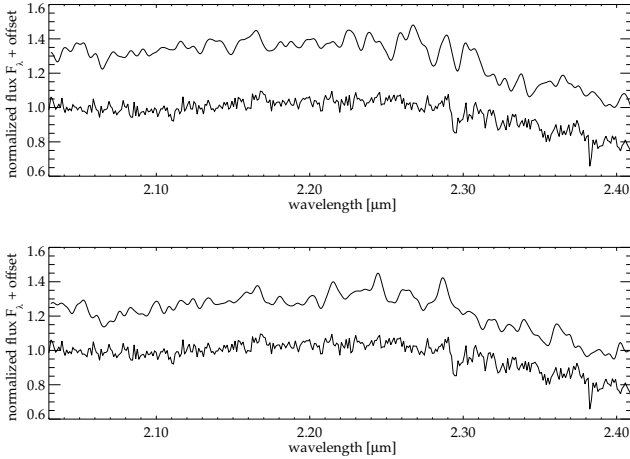


Fig. 8. Observed K-band NACO spectra of the Cha H α 2 system. In each panel, one of the components of the system is shown (top in each panel) compared to the higher S/N spectrum of both objects combined from Fig. 6 (bottom in each panel). Top: Component A (southwestern component). Bottom: Component B (northeastern component). Both spectra are dereddened using the visual extinction of $A_V \approx 4.3$ mag derived from the spectra shown in Fig. 6.

Table 4. Flux ratios of the Cha H α 2 system

JD - 2453400 [days]	Filter	B/A flux ratio
54.62360	Ks	0.931 ± 0.024
382.67884	Ks	0.908 ± 0.014
760.70760	Ks	0.894 ± 0.053
Mean	Ks	0.910 ± 0.019
761.66193	J	0.893 ± 0.040

above ~ 2400 K both models with different treatment of dust formation give the same result at the given temperatures. Our best fit results give an effective temperature of 3000 ± 100 K, a surface gravity $\log g = 4.0^{+0.75}_{-0.5}$ and a visual extinction of $A_V = 4.3 \pm 0.25$ mag, see Fig. 6 and the online material for a color version. We note that our extinction value is in between the A_V of 7.9 mag measured in a slope in the A_V map from Kainulainen et al. (2006) and the first ever measured value of 3.55 mag by Neuhäuser & Comerón (1998). Given the quality of our fit, we find here further evidence for the physical binarity of Cha H α 2 being a double of almost identical mid- to late- M-type objects. If one of the components would be a background (or foreground) object, both the spectral type and the extinction of the components would differ and the unresolved spectrum of the binary would not be consistent with one spectral type over the whole spectral range.

The derived temperature can be converted to a spectral type of $M6 \pm 1$ with the empirical temperature scale for young M-type objects from Luhman (1999). Moreover, our combined spectrum in Fig. 6 resembles very much the spectrum of the M5.75 object ϵ Cha 10 in Luhman (2004).

We also obtained low-S/N (~ 15) K-band spectra of both objects with VLT/NACO, see Fig. 8. They are indistinguishable, giving further evidence that neither of the two objects are background or foreground stars, which would exhibit a significantly different K-band spectrum.

Table 5. Brightnesses of the Cha H α 2 system

Component	J-band	Ks-band
Cha H α 2 A (SW)	12.903 ± 0.033	11.378 ± 0.024
Cha H α 2 B (NE)	13.026 ± 0.035	11.480 ± 0.024

6. Conclusions

From the photometry, the visual extinction, an extinction law to convert the visual to a near-infrared extinction by Rieke & Lebofsky (1985), a bolometric correction BC_K of 3.0 ± 0.1 mag from Golimowski et al. (2004) and the distance to a particular member of the Cha I cloud of 168^{+28}_{-24} from Bertout et al. (1999) (calculated by HIPPARCOS measurements of 4 members of Cha I and resulting in an average distance of 168^{+14}_{-12} to the cloud), we find luminosities $\log(L/L_\odot)$ of -1.21 ± 0.14 & -1.25 ± 0.14 , and radii of $0.92^{+0.19}_{-0.14}$ & $0.88^{+0.18}_{-0.13}$ R_\odot for Cha H α 2 A (SW) and B (NE), respectively. This makes both components more massive than the more massive component of the eclipsing binary brown dwarf found by Stassun et al. (2006) in Orion of $M = 0.054 \pm 0.005 M_\odot$ (assuming similar age, which is justified).

It is, a priori, not known to which of both components the photometric rotation period refers. However, since both stars are very young and have been formed in similar environmental conditions, we may assume that they rotate at the same speed. In this case, we can conclude from the photometric period of 3.21 ± 0.17 days (Joergens et al. 2003) and the $v \sin i$ of 12.8 ± 1.2 km/s (Joergens & Guenther 2001) that Cha H α 2 A and B have inclinations of 36.1 to 143.9 deg and 40.4 to 139.6 deg, respectively, consistent with ~ 65 to 75 deg by Natta et al. (2004). Assuming an alignment of the orbital axis and the rotational axis of both components, this is also consistent with our finding of astrometric orbital motion in the form of a change in separation rather than in a change of the PA, i.e., with an orbital plane being more edge-on than pole-on.

Given the luminosities, temperatures, radii, and gravities, the masses of both components are $0.308^{+1.430}_{-0.231} M_\odot$ and $0.281^{+1.302}_{-0.210} M_\odot$ for A and B, thus leaving Cha H α 2 AB above the stellar – brown dwarf boundary. However, component B could still be a brown dwarf, according to this error estimation. Although we arrive at masses that could possibly be higher than the sun's (given our large error bars), this can be ruled out due to the fact that such very young objects could be of approximately same size as the sun, but would not have a similar surface gravity at the same time. Using theoretical models by Baraffe et al. (1998), we find a best fit for masses of $0.124 M_\odot$ and $0.110 M_\odot$ for Cha H α 2 A and B for an age of 2 Myr, a temperature of ~ 3025 K, a $\log g$ of ~ 3.6 , and the luminosity values as derived above of $\log(L/L_\odot)$ of -1.21 & -1.25 , but we would like to mention that the determination of ages and masses from evolutionary models is uncertain until at least 10 Myrs (Chabrier et al. 2005). These mass values are in good agreement with the mass for the unresolved Cha H α 2 of $0.14 M_\odot$ from Mohanty et al. (2005). While there are currently almost one hundred systems known of even lower total mass (Siegler 2007), a review of the field and the existence of very low mass binaries at different ages can be found in Burgasser et al. (2007).

After submission of our manuscript Ahmic et al. (2007) reported the possible binarity of Cha H α 2 found in their data from 2005, included as 1st epoch in our common proper motion analysis. We note that separation, position angle, and Ks-band magnitudes measured coincide well within the 1σ error bars of each

other. Ahmic et al. (2007) could not show common proper motion because they had only one epoch available.

The projected separation between A and B corresponds to ~ 27 AU at ~ 168 pc, so that further investigation of the interaction between the two components in Cha H α 2 and its disk (with silicate feature) would be very important.

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This research has made use of the VizieR catalogue access tool and the Simbad database, both operated at the Observatoire Strasbourg.

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Online Material

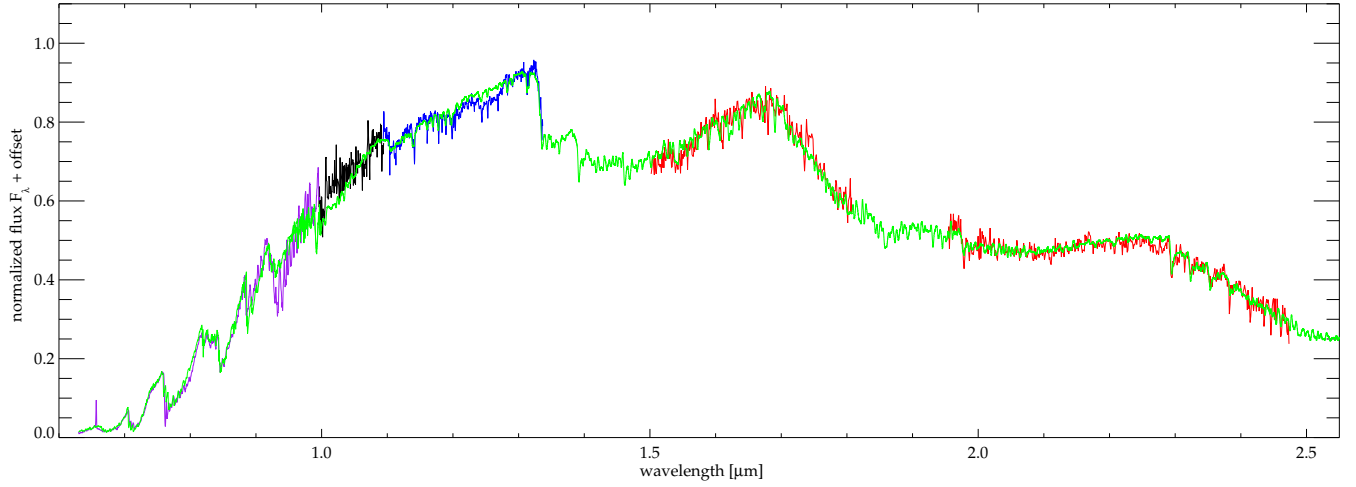


Fig. 6. Spectrum of both components from the optical part to the near-infrared combined from data from Comerón et al. (2000) (purple), and data from the ESO Paranal and La Silla instruments ISAAC (blue) and SofI (black: blue arm spectra, red: red arm spectra) retrieved from the ESO Science Archive Facility. The best fit to the spectrum, a GAIA model computed with the PHOENIX code by Brott & Hauschildt (2005) for a temperature of 3000 K, $\log g$ of 4.0 and a visual extinction of 4.3 is superimposed in green. Note that the missing flux depression in J-band (between 1.2 and 1.3 micron) as well as in the peak of the H-band (around 1.65 micron) is due to missing FeH opacities in the spectral models. Note the strong H α emission in Cha H α 2 at 0.6568 μm .